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A variety of dolphin sonar discrimination experiments have been conducted, yet little is known about the cues utilized by dolphins in making fine target discriminations. In order to gain insights on cues available to echolocating dolphins, sonar discrimination experiments were conducted with human subjects using the same targets employed in dolphin experiments. When digital recordings of echoes from targets ensonified with a dolphinlike signal were played back at a slower rate to human subjects, they could also make fine target discriminations under controlled laboratory conditions about as well as dolphins under less controlled conditions. Subjects reported that time-separation-pitch and duration cues were important. They also reported that low-amplitude echo components 32 dB below the maximum echo component were usable. The signal-to-noise ratio had to be greater than 10 dB above the detection threshold for simple discrimination and 30 dB for difficult discrimination. Except for two cases in which spectral cues in the form of "click pitch" were important, subjects indicated that time-domain rather than frequency-domain processing seemed to be more relevant in analyzing the echoes.

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INTRODUCTION

Many echolocation experiments have been performed to determine the target discrimination capabilities of dolphins (e.g., Nachtigall, 1980; Au *et al.*, 1980; Hammer and Au, 1980). Yet, little is known about how dolphins process echoes or what acoustic cues are being used in making fine discriminations. Targets are usually measured acoustically or analyzed theoretically, either before or after their use in dolphin sonar discrimination experiments. Often, target differences are large and obvious so that little information is gained except that the dolphin can perform the task. Conversely, target differences can be so subtle that we cannot measure them, or we do not know what differences to consider, or we may even overlook important differences.

In this study, we took a different approach in analyzing targets used in dolphin discrimination experiments. We used the excellent discrimination and pattern recognition capabilities of the human auditory system to analyze target echoes and to determine relevant discrimination cues. The human auditory system is still much better than any instrument or computer software presently available in analyzing complex sounds. Furthermore, various psychoacoustic experiments with *Tursiops truncatus* on hearing sensitivity (Johnson, 1967), temporal auditory summation (Johnson, 1968a), critical ratio (Johnson, 1968b), tone-on-tone masking (Johnson, 1971), and frequency discrimination (Thompson and Herman, 1975; Herman and Arbeit, 1976) suggest that the inner ear of dolphins functions similarly to the human inner ear, except for the dolphin's ability to hear much higher frequencies (up to 150 kHz).

We considered two dolphin discrimination experiments in which echoes from targets were subsequently presented to human listeners, and available discrimination cues were examined. The use of the human auditory system in this way is meaningful only if the humans can perform the discrimination task under quiet laboratory conditions as well as dolphins. Fish *et al.* (1976) performed an experiment using human divers instrumented with a broadband sonar that projected dolphinlike signals. They replicated the dolphin experiment of Evans and Powell (1967) in discriminating the composition and thickness of metallic plates and found that the human subjects could perform the discrimination task as well as or better than dolphins. However, the cues used by the subjects were not discussed. Martin and Au (1982, 1986) and Au (1988) have also shown that the human auditory system is well suited to discriminate broadband echoes from targets used in dolphin experiments.

I. MATERIALS AND METHODS

A. Procedure

Target echoes were collected using an HP-2100 minicomputer-controlled monostatic echo measurement system that transmitted a broadband, dolphinlike echolocation signal. A description of the backscatter measurement system was presented by Au and Synder (1980). The incident signal had a duration of approximately 50 μs, a peak frequency of 122 kHz, and a 3-dB bandwidth of 39 kHz. Target echoes were digitized at a sample rate of 1 mHz and stored on magnetic tape. Ten consecutive echoes per target were normally stored on tape and later transferred to disk using a PDP-11 computer system that controlled the human listening experiments.

A pool of six laboratory employees with normal audiograms was used as subjects (five males and one female). Only one subject had previous experiences in psychoacoustic

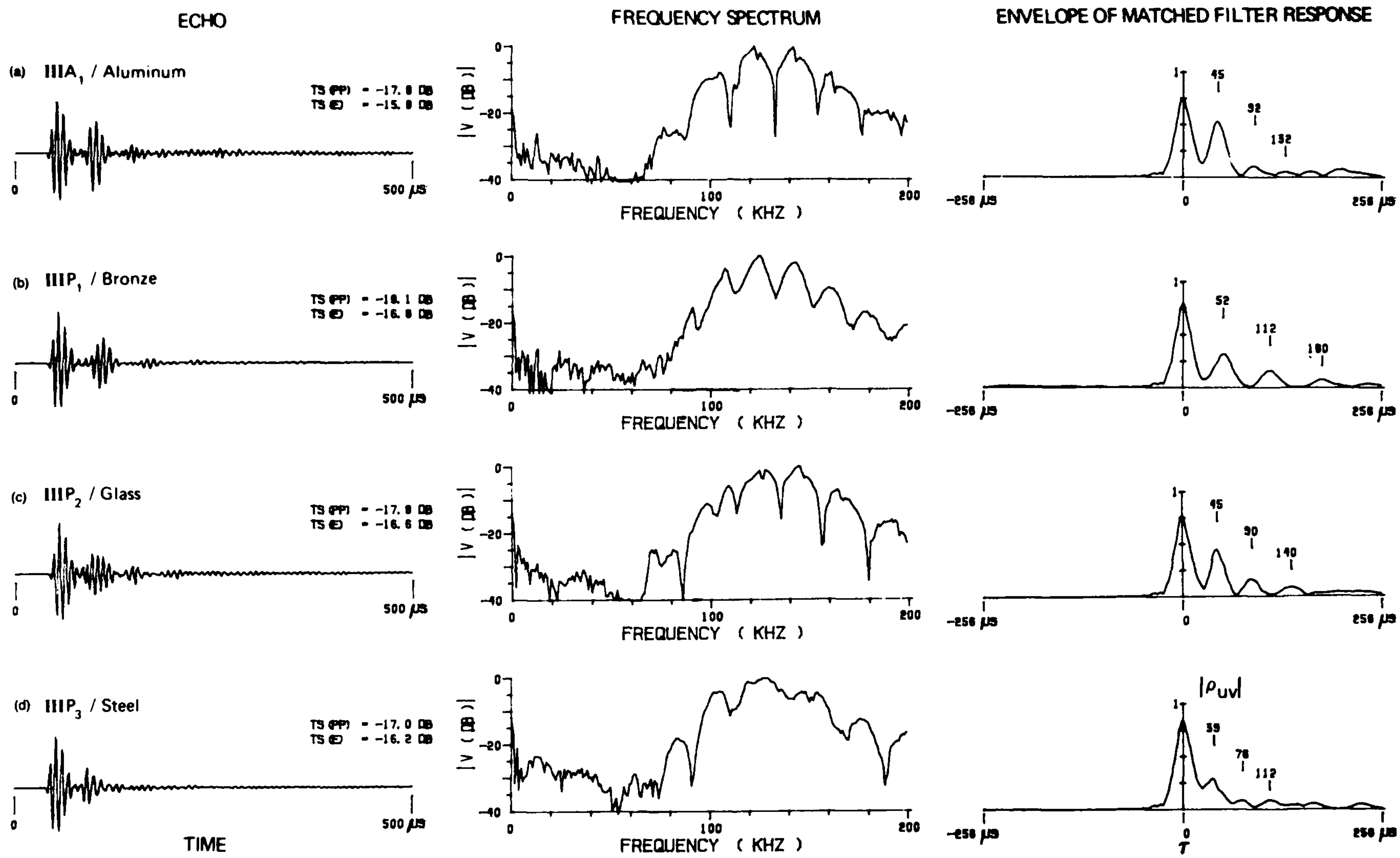

FIG. 1. Results of backscatter measurements on the 3.81-cm-o.d. targets. The echo waveforms, frequency spectra, and matched-filter responses are shown. The target strength TS(pp) was based on maximum peak-to-peak values; TS(E) was based on the energies of the echoes and the incident signal in a 1-ms window. The numbers above the envelope of the matched-filter responses are the time of occurrence of the highlights in μs.

experiments. Their participation was in addition to their normal responsibilities and so their availability was not totally reliable. This resulted in unequal numbers of sessions and trials in the data, which was considered acceptable since the experiments were not involved with the measurement of any basic human psychoacoustic phenomenon. Our primary concerns were to determine if the subjects could perform the various echo discrimination tasks, and to have the subjects describe the cues they felt were important.

The subjects listened to signals in a sound isolation booth (Industrial Acoustics Co.) via Koss ESP-9B electrostatic headphones. Preliminary experiments with nontest echoes indicated that a stretch factor of 50 and a repetition rate of four pulses per second provided the best discrimination performance. The stretch factor is defined as the digitizing sample rate divided by the playback sample rate. With a stretch factor of 50, the original peak frequency of 122 kHz was transformed to 2.4 kHz, and the echo duration was increased by a factor of 50. The signal peak amplitudes were adjusted to be the same so that target strength would not be a discrimination cue.

A typical trial consisted of a subject being presented with prerecorded echoes from either one of two or one of four targets. Subjects were required to classify targets into one of two categories by pressing pushbutton switches labeled A and B. The stimulus was repeated at four pulses per second for 15 s or until the subject responded, whichever occurred first. Failure to respond on any trial was considered an abort. Correct response feedback was provided by lights labeled A and B. In most of the experiments, each target was represented by ten echoes, but only one of them, randomly chosen, was used in a given trial. In a few experiments, only a single echo per target was used. The use of ten echoes per target will be referred to as the MP (multiple-ping) condition and the use of a single-ping per target as the SP condition. Subjects were allowed a warmup period in which they could choose and listen to the A and B signals. The length of the warmup period was determined by the subject. A session consisted of 64 trials with each echo presented an equal number of times in a random order.

B. Cylinder discrimination experiment

The first set of echoes was from the cylinders used in the material discrimination portion of the Hammer and Au (1980) and the Schusterman *et al.* (1980) experiments. Targets were 3.81- and 7.62-cm-o.d. cylinders with the same lengths (17.8 cm) and wall thicknesses (0.32 and 0.40 cm, respectively). They were composed of aluminum, steel, bronze, and glass. The aluminum target echoes were always used as the reference echoes. The echo waveforms, frequency spectra, and matched-filter responses for the targets are displayed in Figs. 1 and 2.

The aluminum versus bronze discrimination was performed with two pairs of targets per material, each pair consisting of a 3.81- and 7.62-cm o.d.-cylinder. Single-ping data were used so that one of four echoes occurred on each trial, and each echo was used in 16 trials per session, randomly distributed. The subjects were required to push switch A to indicate that an echo was from one of the aluminum cylinders or switch B for one of the bronze targets. The aluminum versus steel discrimination was performed in the same manner. Five subjects participated in two sessions, or 128 trials, for each discrimination without any prior training.

The aluminum versus glass discrimination task was performed under three different conditions: (a) single ping with the 3.81-cm-o.d. targets, followed by single ping with the 7.62-cm-o.d. targets; (b) single ping with one of four targets; and (c) multiple pings with the 3.81-cm-o.d. targets followed by multiple pings with the 7.62-cm-o.d. targets. Five subjects participated in three to six sessions under condition (a), three subjects in four to seven sessions under condition (b), and four subjects in three to six sessions under condition (c). The subjects were required to press switch A when they heard echoes from the aluminum cylinders and switch B for the echoes from the glass cylinders.

A further examination of the aluminum versus glass discrimination was performed with echoes from the large targets that were systematically truncated between groups of echo highlights. The signals were progressively made shorter and of equal duration by truncating the signals at the tick marks shown in Fig. 3. Two subjects were tested over three sessions for each pair of truncated signals and their performance with the total signals was also remeasured following testing with the truncated signals.

Several of the material composition discrimination tasks were also performed in white noise. Performance of discrimination tasks in noise can be used to determine the difference in signal-to-noise (S/N) ratios between the point where echoes are just detectable and the point where they can be discriminated. This information is a direct measure of task difficulty and can give insights into the importance of particular discrimination cues.

C. Sphere–cylinder discrimination

The foam spheres and cylinders used in the dolphin discrimination study of Au *et al.* (1980) were next used as targets with the human listeners. Four subjects participated in four sessions. Tests were conducted using both two-target (one sphere and one cylinder) and four-target (two of each) conditions. Discrimination experiments were also conducted with foam target echoes modified by applying a time window to the signals. This time window eliminated an air–water surface reflected component from the echoes. The foam targets and presentation schedules are presented in Table I. Target sizes were chosen such that the target strengths of the two classes overlapped, eliminating target strength as a useful discrimination cue. An example of echoes from one of the foam spheres and cylinders is shown in Fig. 4.

II. RESULTS AND DISCUSSION

A. Cylinder discrimination experiment

The average performance of three subjects in the aluminum versus bronze and in the aluminum versus steel discrimination was 98 and 95 percent correct, respectively. The subjects all reported that they first determined whether an echo originated from a large or small cylinder based on a duration cue. Echoes from the large cylinder had longer du-

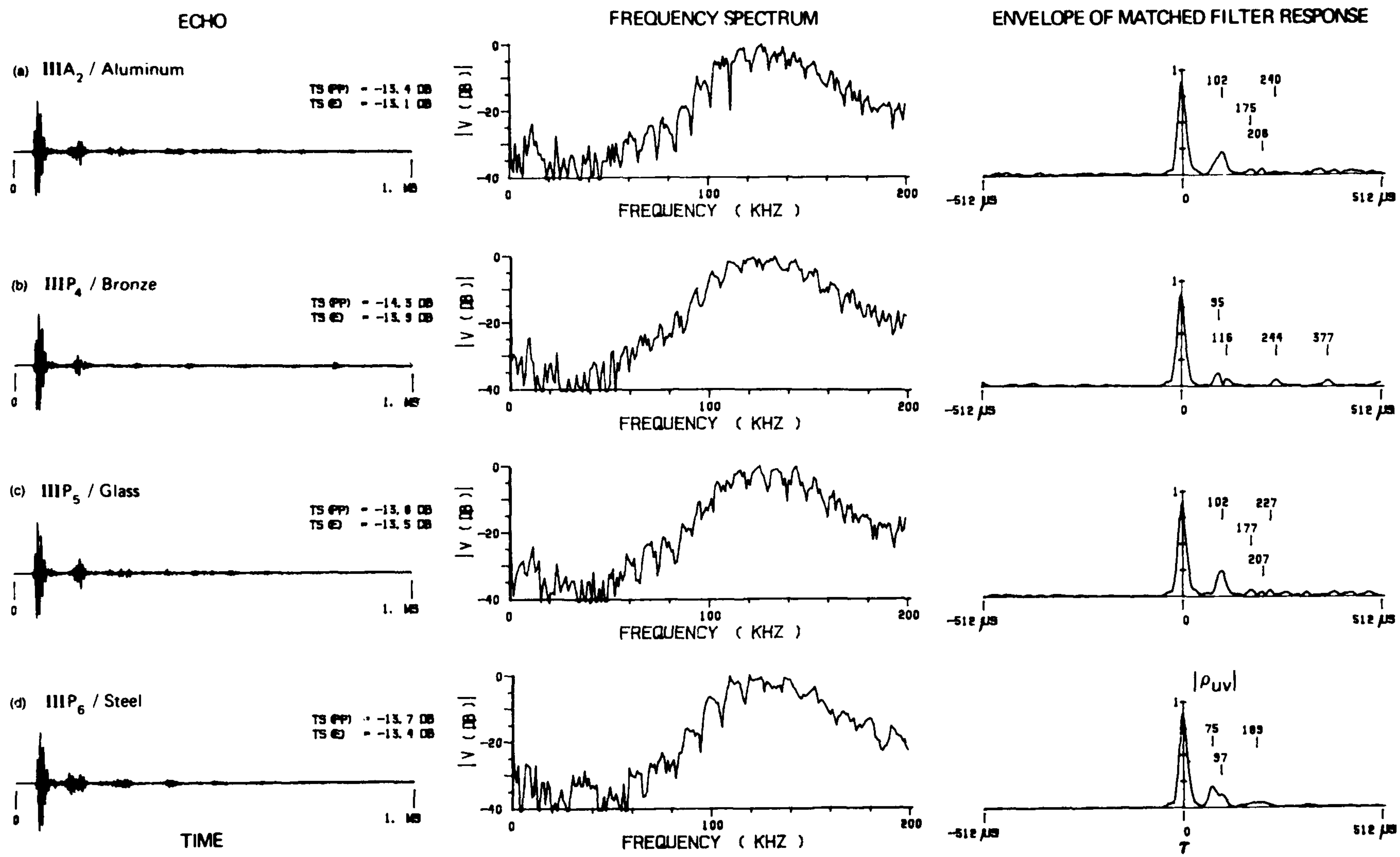

FIG. 2. Results of backscatter measurements of the 7.62-cm-o.d. targets.

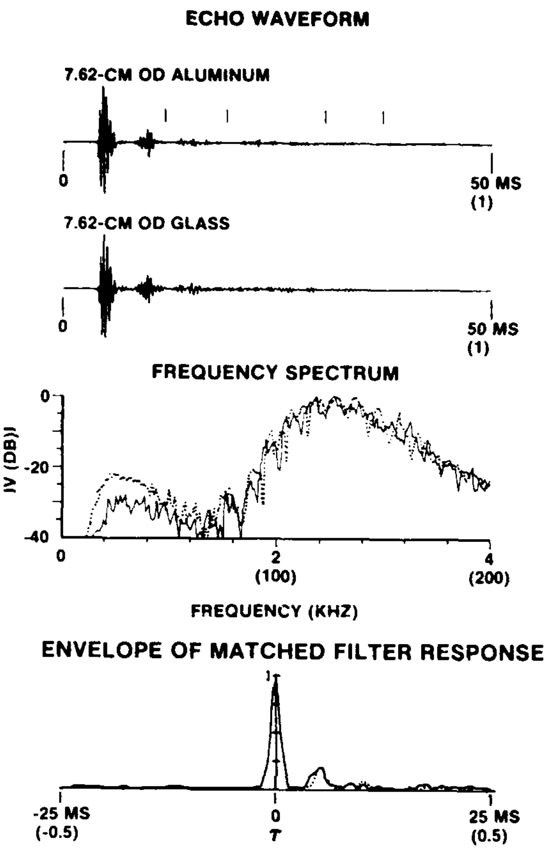

FIG. 3. Typical echo waveforms, frequency spectra, and matched-filter responses for the 7.62-cm aluminum and glass cylinder. The solid spectrum is for the aluminum cylinder, and the dotted spectrum is for the glass cylinder. The tic marks shown above the aluminum echo indicate where the signals were truncated.

rations. Subjects reported that discrimination between the small aluminum and bronze cylinders was based on the presence of a lower time-separation pitch (TSP) in the bronze than in the aluminum. From the envelope of the matched-filter response in Fig. 1, we can see that the time separation between the first and second echo components was 52 μs for the small bronze cylinder and 45 μs for the small aluminum cylinder. After stretching the signals by a factor of 50, the resulting TSP should be 385 Hz for the bronze and 444 Hz for the aluminum. The subjects reported that discrimination

TABLE I. Foam targets and presentation schedules. The dimensions of the foam spheres (diameter) and cylinders (diameter × length) are as used in the shape discrimination test.

Spheres	Cylinders	Presentation schedule		
S1:10.2 cm	C1:1.9 × 4.9 cm	S2	vs	C4
S2:12.7cm	C2:2.5 × 3.8 cm	S2 and S3	vs	C3 and C4
S3:15.2 cm	C3:2.5 × 5.1 cm	S1 and S3	vs	C1 and C5
	C4:3.8 × 5.4 cm	S1 and S2	vs	C4 and C5
	C5:3.8 × 5.1 cm	S1 and S2	vs	C2 and C4

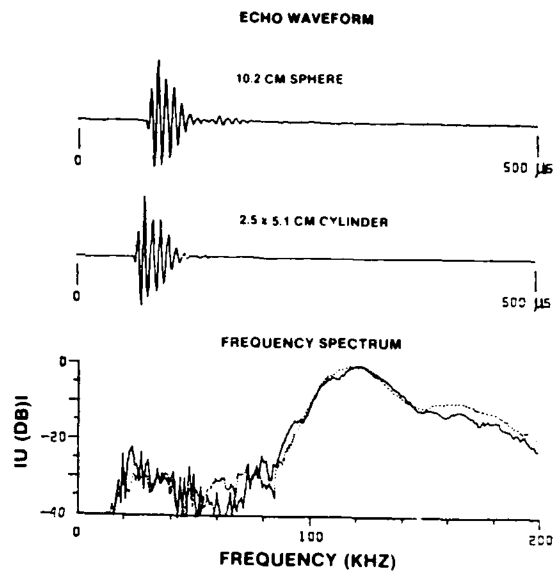

FIG. 4. Typical echo waveforms and frequency spectra for foam sphere and cylinder used in the shape discrimination test. The solid spectrum is for the sphere, and the dotted spectrum is for the cylinder. The dimensions are diameter for the sphere and diameter × length for the cylinder.

between the large aluminum and bronze cylinders was based on the presence of TSP with the aluminum cylinder and the absence of TSP with the bronze cylinder. Figure 2 shows that there is interference between the second and third echo components in the bronze target, which may have affected the perception of TSP.

The subjects reported that the aluminum–steel discrimination was made on the basis of clearly perceptible TSP with both the small and large aluminum cylinder echoes. The presence of TSP was not as definite for the steel cylinders. The envelope of the matched-filter responses in Figs. 1 and 2 suggests that the aluminum targets should produce clearer TSPs since the first and second highlights were more highly corrected.

The results of the aluminum versus glass discrimination task are shown in Table II. These results represent data obtained after the subjects' performances stabilized. Large differences between subjects in the ability to discriminate the target echoes are apparent. The data indicate that all of the subjects could discriminate between aluminum and glass with performance accuracy varying between 72.3 and 97.9 percent correct. Performance was not degraded by transferring from a one-of-two-targets to a one-of-four-targets task using single-ping information. However, the transfer from the use of single-ping to multiple-ping information resulted in a decrease in accuracy for most of the subjects, and the amount of decrease was subject dependent. The subjects indicated that the echoes from the aluminum and glass targets sounded very similar and that the introduction of variances due to multiple pings made the task more difficult.

The reported discrimination cue was the difference in echo durations between the aluminum and glass echoes for both the small and large targets. From Fig. 3, we can see that

TABLE II. Results of the aluminum–glass discrimination task for different conditions.

Subject	3.81-cm-o.d. cylinder No. trials	3.81-cm-o.d. cylinder % correct	7.62-cm-o.d. cylinder No. trials	7.62-cm-o.d. cylinder % correct
	Single ping—one of two targets			
DM	192	94.3	256	94.5
KD	192	95.3	191	97.9
PT	318	87.7	256	93.4
DS	384	75.8	382	72.3
GP	384	74.7	382	74.9
	Single ping—one of four targets			
DM	210	92.9	210	95.2
KD	139	96.2	125	97.0
PT	191	86.4	193	97.9
	Multiple ping—one of two targets			
DM	384	85.2	384	94.3
KD	256	88.3	192	84.4
PT	384	74.0	384	78.4
GP	320	76.6	192	76.6

the echoes from the glass targets damped out sooner than echoes from the aluminum targets. Visual inspection of the small-target echoes indicates that the glass echo damped out approximately 14 ms (0.28 ms before stretching) before the aluminum echo. For the larger targets, the glass echo damped out approximately 5 to 7 ms (0.10 to 0.14 ms before stretching) before the aluminum echo. Schusterman *et al.* (1980) trained the dolphin to perform the small aluminum–glass discrimination, but could not train the animal to perform the large aluminum–glass discrimination. The duration difference of 0.10 to 0.14 ms may not have been perceptible to the animal but could be perceived by humans because the signals were expanded in time by a factor of 50. It may also be possible that the animal could not detect duration cues because these cues are contained in the portion of the signals that are approximately 32 dB below the peak and may have been masked by the ambient noise of the bay. A third possibility for the dolphin is that the initial peaks in the echoes could have forward masked later portions of the echo (Resnick and Feth, 1975), since the total echo duration is approximately 0.5 to 1.0 ms.

The results of the experiment in which the aluminum and glass echoes were systematically truncated (see Fig. 3) are shown in Fig. 5. Discrimination accuracy decreased as the signals were truncated, with the exception of one data point for subject PT. The figure also conveys the importance of the duration cues, since performance accuracy decreased when the signal durations were made the same upon the first truncation. Because the tail portion of the aluminum echo was approximately 32 dB below the level of the primary echo component, the subjects were probably using information over a 32-dB dynamic range before truncation.

Performance remained significantly above chance after the duration cue was eliminated upon the first truncation, and remained above chance with further truncations. The final truncation eliminated all but the first two echo components, yet the subjects were able to discriminate the signals above 70 percent correct. The time between the first and second echo components is virtually the same for both targets; thus the discrimination probably was based on cues other than differences in TSP. The subjects indicated that the glass target had a slightly higher "click pitch" than the aluminum target when using the truncated signals. Click pitch is defined here as the pitch associated with the peak frequency of a broadband transient signal. It was also reported that this cue was difficult to extract and was not always reliable. By examining the frequency spectra of Fig. 3, we can see that the minima for frequencies above 1.8 kHz for the glass spectrum is approximately 67 Hz higher than that of the aluminum spectrum. Although Fig. 3 shows the spectra of the total signals, the spectra for the first and second echo components were shown by Hammer and Au (1980) to be similar to the total echo spectra.

The frequency spectra shown in Figs. 1–3 were obtained by taking the Fourier transform of the total signal shown in each figure. However, the mammalian ear does not function

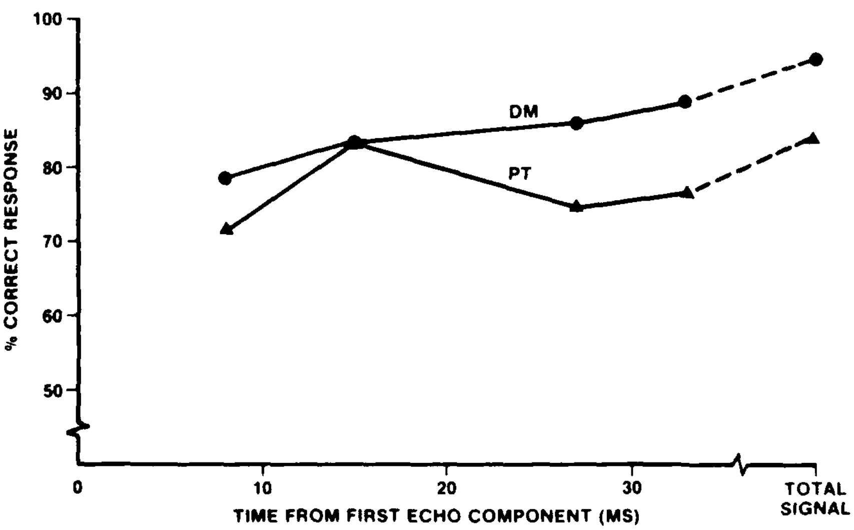

FIG. 5. Discrimination performance results with the 7.62-cm aluminum and glass cylinders as a function of the echo duration.

like the mathematical model used to obtained the frequency spectra. The ear analyzes a signal as it is received, not waiting until the "total" signal is received. Therefore, in order to obtain a more realistic interpretation of the experimental results, echoes from the aluminum and glass cylinders were subjected to a short-time spectral analysis following Johnson *et al.* (1988). The same chi-square window used by Johnson *et al.* (1988) in analyzing the results of a dolphin auditory experiment was also used, and the spectra of the echoes were computed at fixed intervals as echoes slid past the window. The results for the 3.81-cm-o.d. and the 7.62-cm-o.d. cylinders are shown as waterfall displays in Figs. 6 and 7, respectively. The spectra were obtained at 25-μs increments for the 3.81-cm cylinders and at 37.5-μs increments for the 7.62-cm cylinders. The relative amplitude of the peak excursion of each spectrum is shown in the spectral plots.

The waterfall displays in Fig. 6 indicate that the spectra for the 3.81-cm aluminum and glass cylinders were very similar for times between 25 and 75 μs. For times of 100 μs and greater, the spectra for the two cylinders show small but observable differences. The spectra for the glass target are shifted slightly toward higher frequencies, and the ripples are less regular than for the aluminum target. However, these spectral differences were not reported by the subjects suggesting that the reported duration difference cue dominated the spectral differences in the decision process.

The waterfall displays for the 7.62-cm cylinders in Fig. 7 indicate that the spectra for both cylinders were much more similar than for the 3.81-cm cylinders. Subtle differences can be seen in the spectra; however, these differences are very slight. The ripple intervals for both cylinders were nearly identical. The spectra for the glass cylinder are shifted slightly toward higher frequencies in a similar manner as were the total spectra shown in Fig. 3. This can be seen by overlaying one waterfall display over the other. The results of the short-time spectral analysis for the 7.62-cm cylinders seem to be consistent with the subject's observation of higher "click" pitch associated with the glass cylinder after the duration cue was eliminated.

The differences between the discrimination and detection thresholds measured in the experiment with white noise are listed in Table III. Simple discriminations such as the aluminum–bronze and the 3.81-cm-o.d. aluminum–glass discriminations required S/N ratios 7 to 11 dB above the detection threshold to obtain 75 percent correct. For the most difficult material discrimination, 7.62-cm-o.d. aluminum versus glass cylinders, an S/N ratio 21 to 30 dB above the detection threshold was required for 75 percent correct discrimination.

B. Sphere–cylinder discrimination

Discrimination results pooled across the four subjects for the foam targets are shown in Table IV. The averages of the percent correct discrimination varied between 84 and 96 percent correct for the unwindowed echoes. With one exception, variations in individual's scores were within 3% of their mean scores. For the comparison, S1 and S2 vs C4 and C5, individual scores varied between 76 and 91 percent correct.

Subjects reported using two cues for these discriminations: a higher pitch for cylinder echoes and larger low-fre-

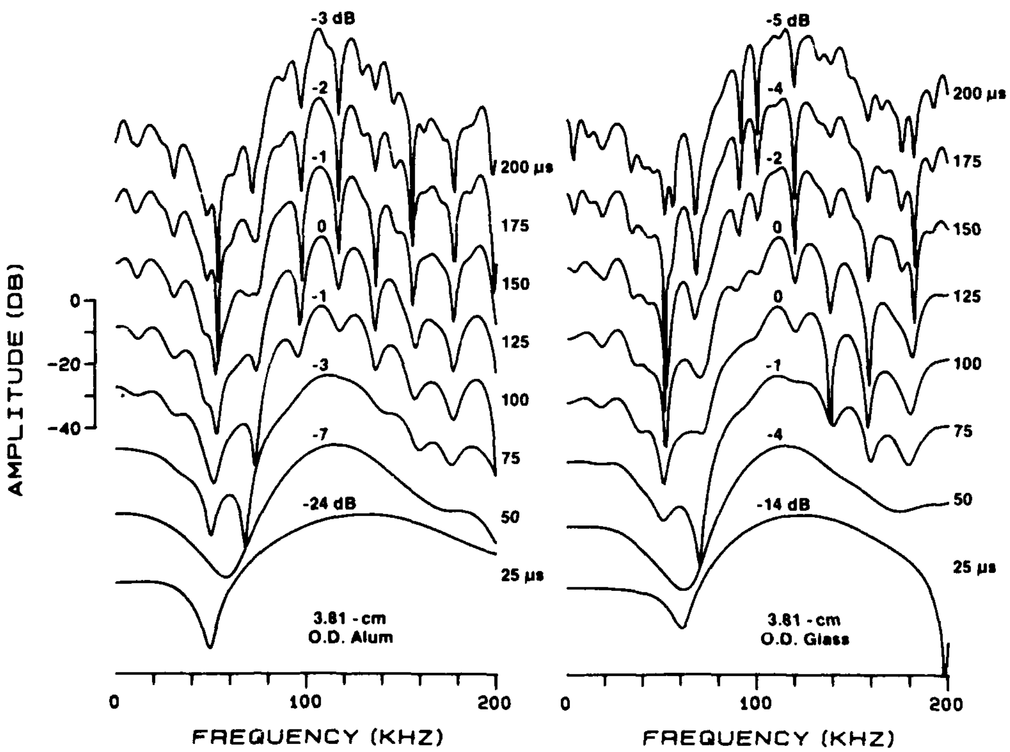

FIG. 6. Results of the short-time spectral analysis performed on the 3.81-cm-o.d. cylinders. On the right side of each waterfall display is the time corresponding to the starting position of the chi-square window. The relative amplitude of the maximum excursion of each spectrum in dB is shown close to the peak of each spectrum.

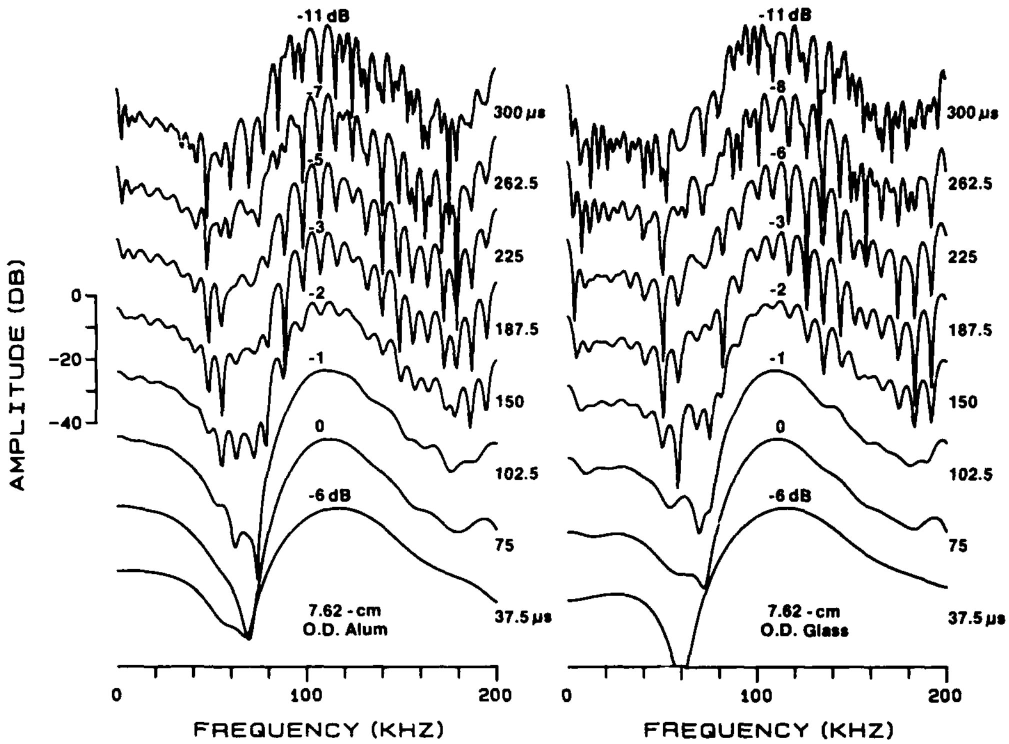

FIG. 7. Results of the short-time spectral analysis performed on the 7.82-cm-o.d. cylinders. On the right side of each waterfall display is the time corresponding to the starting position of the chi-square window. The relative amplitude of the maximum excursion of each spectrum in dB is shown close to the peak of each spectrum.

quency reverberation in the sphere echoes. The pitch difference probably occurs because the target strength of a finite cylinder at normal incident increases with frequency and is constant for a sphere (Urick, 1983). The low-frequency reverberation resulted from acoustic energy reflecting off the target toward the surface and bouncing off the surface air–water interface back toward the transducer.

Au *et al.* (1980) originally attributed the dolphin's discrimination performance to the stronger surface-reflected component in the sphere echoes as compared with the cylinder echoes. However, when a session was conducted in which the surface-reflected component was blocked with a "horsehair" mat, the dolphin still performed the task at 100 percent correct. For test with echoes that had no surface-reflected component, the subjects' discrimination performance dropped an average of 8% (windowed data of Table IV). However, performance exceeded 80 percent correct on all tasks considered. The reverberation was helpful but not necessary for discrimination.

III. SUMMARY AND CONCLUSIONS

The capabilities of human subjects to perform complex target discriminations using broadband-simulated dolphin echolocation signals were determined by examining echoes from targets used in two dolphin echolocation experiments. Human subjects could not only make fine discriminations of target structure, size, shape, and material composition but could also provide feedback about the cues used in making the discrimination. Human subjects listened to the echoes played at one-fiftieth of the original sample rate during two-alternative forced-choice target discrimination tests. Echo waveforms contained highlights from multiple internal reflections, with differences in highlight arrival times determined by acoustic-path-length differences in the targets.

Differences in time-separation pitch associated with correlated echo highlights were the predominant discrimi-

TABLE III. Difference in S/N ratio between the 75 percent correct response thresholds for detection and discrimination. An average detection threshold of 10.5 dB was used for all cylinders.

Task	DM	PT	RB
Hollow aluminum versus glass: 7.62-cm o.d.	24 dB	30 dB	21 dB
Hollow aluminum versus glass: 3.82-cm o.d.	11 dB	···	···
Hollow aluminum versus bronze: 3.81-cm o.d.	7 dB	···	11 dB

TABLE IV. Sphere versus cylinder discrimination performance results with the foam targets. The windowed results refer to echoes for which the air–water surface-reflected components in the echoes were eliminated. The results are the average from four subjects, with 256 trials per subject.

Task	Total echoes (% correct)	Windowed echoes (% correct)
S2 vs C4	96	88
S2 and S3 vs C3 and C4	93	85
S1 and S3 vs C1 and C5	88	81
S1 and S2 vs C4 and C5	84	···
S1 and S2 vs C2 and C4	91	83

nation cues in all of the tasks except the truncated aluminum versus glass cylinders and spheres versus cylinders discrimination. Acoustic signals that evoke TSP in humans have frequency spectra that contain periodic ripples. Au and Pawloski (1989) have shown that dolphins can discriminate between broadband noise signals having rippled spectra from nonrippled noise, suggesting that dolphins may be able to perceive TSP. In those cases in which TSP was not a factor, differences in "click pitch" seemed to be the dominant cue. In the most difficult discrimination involving the 7.62-cm-diam aluminum and glass cylinders, difference in echo duration was the predominant discrimination cue. The duration information was approximately 32 dB below the peak level of the primary echo component, which may explain why the dolphin could not perform this discrimination in Kaneohe Bay, which is a high-noise environment due to the presence of snapping shrimp.

Discrimination tests in noise showed that simple tasks such as the 3.81-cm-o.d. aluminum versus bronze and the 3.81-cm-o.d. aluminum versus glass cylinders discriminations required S/N ratios about 10 dB above the detection threshold for 75 percent correct discrimination. Difficult tasks such as the 7.62-cm-o.d. aluminum–glass cylinder discrimination required about a 30-dB difference between the 75 percent detection and discrimination thresholds.

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